

Technological Overview: Analysis of Patents Related to the Use of Core-Shell Catalysts and ALD in Solid Oxide Fuel Cells

Iuri Dantas Passos da Mota^{1*}, Marcos Makoto Toyama^{1,2}, Gerhard Ett^{1,3}, Lilian Lefol Nani Guarieiro¹

¹SENAI CIMATEC University; Salvador, Bahia; ²Mauá Institute of Technology; São Caetano do Sul, São Paulo; ³FEI University Center; São Bernardo do Campo, São Paulo, Brazil

This study analyzes patents registered between 2010 and 2025 involving solid oxide fuel cells (SOFC), atomic layer deposition (ALD), and core-shell structures. Data from Lens.org show that the combination of ALD and core-shell accounts for the largest number of registrations, reflecting broad industrial applicability. Combinations with SOFCs, on the other hand, have a low incidence, suggesting an area in the early stages of intellectual property protection. Only two registrations simultaneously associate SOFC, ALD, and core-shell, evidencing a little-explored technological frontier. Most filings occur in the US, Japan, South Korea, and the European Patent Office (EPO), with an emphasis on companies and research institutions. Brazil's presence is limited to one registration involving SOFC and core-shell, indicating the need for greater investment in applied research and intellectual property protection. The interface between these technologies represents an emerging niche with high innovative potential.

Keywords: SOFC. Core-shell. ALD. Sustainability. Solid Oxide Fuel Cells. Atomic Layer Deposition. Patent.

Fuel cells are efficient electrochemical devices that produce electricity through redox reactions, making them a clean energy alternative [1,2]. The development of SOFCs had milestones such as the discovery of solid electrolytes by Nernst (1892) and the first ceramic cell by Baur and Preis (1936) [3]. They stand out among high-temperature types, classified according to the electrolyte and operating range [4,5].

SOFCs, made with solid ceramic materials, operate between 800 and 1000 °C, favoring the kinetics of reactions with high efficiency and without noble metals [6,7]. This configuration allows flexibility in design and fuel choice [5]. Operation is based on fuel oxidation at the anode, oxidant reduction at the cathode, oxygen ion conduction through the electrolyte, and current generation in the external circuit.

Core-shell nanoparticles are composed of a core coated with one or more outer layers of another material [8,9]. The convention for naming them uses the symbol “@,” reflecting the sequence of

the layers that compose them [10]. According to Gawande and colleagues (2015) [11], the classification can also take into account the nature of the material, organic or inorganic, and the morphological characteristics of the shell, such as porosity, number of layers, or presence of cavities, factors that directly influence their properties and applications.

The ALD technique, developed in the 1970s and widespread after 2000, allows the deposition of ultra-thin films (<20 nm) with high uniformity, even on complex surfaces [12–15]. It is based on sequential and self-limiting chemical reactions, allowing precise thickness control. Its main variations are thermal ALD (ThALD) and plasma-enhanced ALD (PEALD), the latter enabling film growth at lower temperatures [12,16,17].

In this context, this study analyzes patents related to SOFCs, focusing on the application of core-shell catalysts and the ALD technique. The investigation continues a previous bibliometric analysis, expanding the scope to the field of intellectual property. Based on this approach, we seek to observe the transition from scientific knowledge to technological applications, identify innovation trends, main depositors, and areas with industrial potential. To this end, patents indexed in the Lens.org database are analyzed, using its

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Address for correspondence: Iuri Dantas Passos da Mota. Av. Orlando Gomes, 1845 - Piatã, Salvador – BA – Brazil, Zipcode: 41650-010. E-mail: iuri.mota@fbter.org.br.

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analytical tools to map technological advances, identify gaps, and highlight innovations in the use of these technologies in solid oxide fuel cells.

Materials and Methods

The technological prospecting was carried out by collecting and analyzing patents available on the Lens.org database (<https://www.lens.org>), using the platform's own analytical tool. The main indicators are summarized in Table 1. The search was conducted in July 2025 and covered patents granted between 2010 and 2025. The year 2010 was adopted as the starting point in order to maintain consistency with a previous bibliometric investigation, conducted by the author, which addressed the same thematic area.

Four combinations of keywords were applied: “Solid Oxide Fuel Cell” AND “Atomic Layer Deposition”; “Solid Oxide Fuel Cell” AND “core-shell”; “Atomic Layer Deposition” AND “core-shell”; and the triple combination “Solid Oxide Fuel Cell” AND “Atomic Layer Deposition” AND “core-shell”, resulting in 17, 7, 39, and 2 records, respectively.

Although the triple combination resulted in only two records, this group should not be disregarded, as

it includes patents with links to scientific literature through citations to non-patented sources (NPL) and presents relevant indicators of technological impact. This suggests that the integration of the three topics, still largely unexplored, represents an emerging field with strategic potential in the development of innovative solutions for SOFC.

Results and Discussion

Annual Patents Production

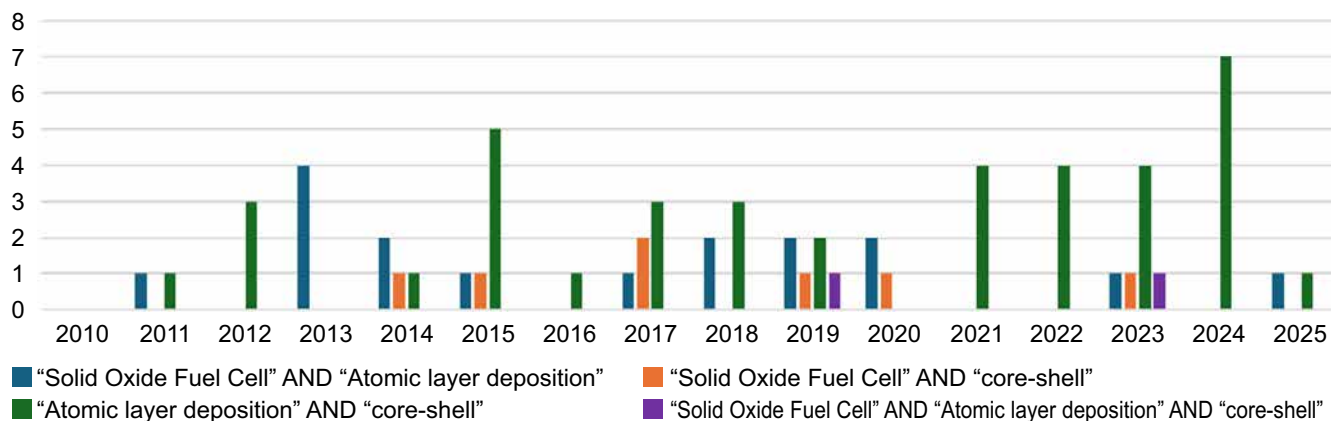
Figure 1 shows the annual evolution of patents published between 2010 and 2025 related to the terms “Solid Oxide Fuel Cell,” “core-shell,” and “Atomic Layer Deposition” in different combinations. The association between “Atomic Layer Deposition” and “core-shell” stands out, with the highest number of registrations in the period, peaking in 2024 with seven filings and remaining relatively stable since 2015. This pattern indicates technological consolidation in the use of core-shell structures of the ALD technique, with potential applications in various sectors, including SOFC.

In contrast, combinations with the term “Solid Oxide Fuel Cell” show a lower volume. The

Table 1. Patent data extracted from the Lens.org database with different thematic combinations.

Description	“SOFC” AND “ALD”	“SOFC” AND “Core-Shell”	“ALD” AND “Core-Shell”	“SOFC” AND “ALD” AND “Core-Shell”
Patent Registration	17	7	39	2
Simple Families	14	7	33	2
Extended Families	14	7	33	2
Patent Citations	17	4	36	2
Cited by Patents	7	2	19	2
Patent Citations	11	2	155	2
NPL Citations	10	3	28	2
NPL Citations	66	35	297	34
Resolved NPL Citations	27	12	211	11

Figure 1. Annual evolution of the number of patents published between 2010 and 2025, considering combinations of the terms “Solid Oxide Fuel Cell,” “Atomic Layer Deposition,” and “core-shell”.



relationship with “Atomic Layer Deposition” peaked in 2013 but remained irregular. The combination with “core-shell” shows sporadic deposits, with no trend toward continuous growth. The more specific search, which combines the three terms, resulted in only two records, published in 2019 and 2023. The low occurrence indicates that this integration is still under-explored technologically, characterizing a specific niche, with limited interest and no signs of consolidation.

Main Patent Applicants

Table 2 lists the main patent filers for each combination of terms analyzed, highlighting the diversity of actors involved in the development of technologies related to SOFC, core-shell, and ALD, with variations according to the thematic focus.

In the combination “Solid Oxide Fuel Cell” and “Atomic Layer Deposition,” Roeder Jeffrey F and Sonata Scient LLC stand out, with 5 registrations each, followed by Stanford University, with 4. The presence of academic institutions and individual researchers suggests strong involvement in applied research.

In turn, the combination of “Solid Oxide Fuel Cell” and “core-shell” presents a more dispersed panorama. The Korea Ceramic Technology

Institute leads with 2 deposits, while the others appear with only 1 registration each. This pattern suggests a still incipient stage of development or a more specific interest on the part of the institutions involved.

In the combination of “Atomic Layer Deposition” and “core-shell,” there is greater diversity of depositors, including companies and research centers. Sila Nanotechnologies INC and US Gov Sec Navy lead with four registrations, followed by Cellmobility INC, Nanosys INC, and Samsung with two. Other participants appear with isolated contributions. This distribution reinforces the technological potential of ALD application and core-shell structures, arousing significant interest, especially in the industrial sector.

In the more specific combination, with the three terms, all depositors appear with only one patent. Among them are Roeder Jeffrey F, Sonata Scient LLC, Van Buskirk Peter C, and Univ Colorado Regents. The absence of a dominant group or institution in this thematic combination indicates that the overlap of the three topics is still the subject of sporadic and scattered investigations.

Overall, the analysis shows a fragmented scenario, with few recurring applicants. This dispersion reflects both the variety of applications and the emerging nature of the integration between SOFC, ALD, and core-shell structures.

Table 2. Distribution of the main patent filers by combination of terms.

“SOFC” AND “ALD”		“SOFC” AND “core-shell”		“ALD” AND “core-shell”		“SOFC” AND “ALD” AND “core-shell”	
Dep	Doc	Dep	Doc	Dep	Doc	Dep	Doc
Roeder Jeffrey F	5	Korea Ceramic Technology Institute	2	Sila Nanotechnologies INC	4	Roeder Jeffrey F	1
Sonata Scient LLC	5	Coppe Ufrj	1	Us Gov Sec Navy	4		
Univ Leland Stanford Junior	4	Korea Inst Ceramic Eng & Tech	1	Cellmobility INC	2	Sonata Scient LLC	1
Van Buskirk Peter C	4	Nissan North America INC	1	Nanosys INC	2		
Honda Motor CO LTD	3	Roeder Jeffrey F	1	Samsung Electronics CO LTD	2	Univ Colorado Regents	1
Prinz Friedrich B	3	Sonata Scient LLC	1	Ajou Univ Industry—academic Cooperation Foundation	1		
Zeberoff Anthony F	3	Univ Colorado Regents	1	Avantama AG	1	Van Buskirk Peter C	1
Sumitomo Metal Mining CO	2	Van Buskirk Peter C	1	Becker Carsten	1		
Univ Colorado Regents	2	Zeberoff Anthony F	1	Benayad Anass	1	Zeberoff Anthony F	1

Dep, Depositors; Doc, Documents.

Geographical Distribution of Inventors

Table 3 shows the countries with the highest number of inventors linked to patents for different combinations of “Solid Oxide Fuel Cell,” “Atomic Layer Deposition,” and “core-shell.” The United States and South Korea predominate, reflecting their leadership in research and innovation.

In the combination of “Atomic Layer Deposition” and “core-shell,” the US leads with 23 inventors, followed by South Korea [10]. Other countries appear with occasional participation,

such as Switzerland, China, Germany, France, Israel, the Netherlands, and Taiwan, highlighting a broad international scenario, with emphasis on the US, Asia, and Europe.

In the combination of “Solid Oxide Fuel Cell” and “Atomic Layer Deposition,” the US also leads with 12 inventors, followed by Japan, Estonia, Finland, and South Korea, with smaller shares. In the association between “Solid Oxide Fuel Cell” and “core-shell,” the US has three inventors, followed by South Korea and Brazil, with one inventor each. The Brazilian presence, although

Table 3. Geographic distribution of inventors by country, considering combinations of the terms “Solid Oxide Fuel Cell,” “Atomic Layer Deposition,” and “core-shell”.

“SOFC” AND “ALD”		“SOFC” AND “core-shell”		“ALD” AND “core-shell”		“SOFC” AND “ALD” AND “core-shell”	
Country	Documents	Country	Documents	Country	Documents	Country	Documents
United States	12	United States	3	United States	23	United States	2
Japan	3			South Korea	10		
Estonia	1			Switzerland	2		
		South Korea	1	China	1		
				Germany	1		
Finland	1			France	1		
South Korea	1	Brazil	1	Israel	1		
				Netherlands	1		
				Taiwan	1		

isolated, suggests an opportunity for insertion in technological development related to this specific area. The most restricted combination, involving the three terms, has only two inventors, both from the US, confirming that this integration is still under-explored in patents.

Brazil appears only in the combination “Solid Oxide Fuel Cell” and “core-shell,” with no records in the others. This points to limited participation in the generation of intellectual property in these areas, but also to a strategic opportunity for action, such as a strategy to boost applied research, foster international collaborations, and expand Brazil's presence.

In general, the data reinforce the leading role of the US and South Korea in the advancement of these technologies, while other countries contribute in a sporadic manner, composing a global panorama of development.

Main CPC Classification Codes

Table 4 shows the most recurrent cooperative patent classification (CPC) codes in patents

resulting from different combinations of “SOFC”, “ALD” and “core-shell”. These codes group patents by technological areas, allowing the identification of the main areas of development.

In the combination of “SOFC” and “ALD”, the codes Y02E60/50 (17 records), focused on technologies for reducing greenhouse gas emissions, and Y02P70/50 (11 records), related to sustainable industrial processes, stand out. Also noteworthy are classifications related to SOFC and zirconium oxide electrolytes (H01M2008/1293 and H01M8/1253), as well as codes for chemical vapor deposition (C23C16/405 and C23C16/45555).

In the combination “SOFC” and “core-shell,” the most frequent codes include Y02E60/50, H01M2008/1293, and H01M4/8657, the latter associated with layered electrodes, indicating a focus on sustainable electrochemical devices.

For “ALD” and “core-shell,” codes related to surface engineering and ultrathin coatings predominate, such as C23C16/45555, C23C16/403 (aluminum, magnesium, or beryllium coatings), and C23C16/4417

Table 4. Top ten CPC codes identified in the combinations of terms analyzed.

“SOFC” AND “ALD”		“SOFC” AND “core-shell”		“ALD” AND “core-shell”		“SOFC” AND “ALD” AND “core-shell”	
CPC	Q	CPC	Q	CPC	Q	CPC	Q
Y02E60/50	17	Y02E60/50	6	B82Y30/00	8	H01M2008/1293	2
Y02P70/50	11	H01M2008/1293	5	C23C16/45555	8	Y02E60/50	2
H01M2008/1293	10	H01M4/8657	4	C23C16/403	7	A61K6/818	1
H01M8/1253	7	H01M4/86	2	Y02E60/50	7	A61K6/822	1
C23C16/405	6	H01M4/8885	2	C23C16/4417	6	B33Y70/00	1
C23C16/45555	6	H01M8/12	2	C23C16/45525	6	C04B2235/3217	1
H01M4/8867	5	Y02P70/50	2	C04B2235/3217	5	C04B2235/3225	1
C23C16/40	4	A61K6/818	1	C04B35/62813	5	C04B2235/3229	1
H01M4/9058	4	A61K6/822	1	C04B35/62884	5	C04B2235/3232	1
H01M8/1246	4	B33Y70/00	1	C23C16/405	5	C04B2235/3246	1

Q, Qunatity.

(powder materials), in addition to B82Y30/00, focused on the application of nanotechnology in materials.

In the combination of the three terms, despite the small number of patents, codes H01M2008/1293 and Y02E60/50 stand out again, indicating a focus on electrochemical devices with a positive environmental impact.

In summary, the data point to a variety of technological areas, with an emphasis on clean energy, sustainable processes, electrochemistry, and nanotechnology, reflecting the interdisciplinary nature and high potential of the technologies analyzed.

Legal Status of Patent Documents

Table 5 shows the legal status of patents in different combinations of “SOFC,” “ALD,” and “core-shell,” classifying them as active or inactive. The combination of “ALD” and “core-shell” has the highest number of active patents (33), indicating a growing field with significant technological potential.

In contrast, “SOFC” and “ALD” are dominated by inactive registrations (12), suggesting a previous phase of activity or a recent decline in interest. The combination of “SOFC” and “core-shell” is balanced, with 5 active and 2 inactive patents, pointing to possible recent consolidation.

In the combination of the three terms, there are only 2 documents: 1 active and 1 inactive, which reinforces the initial and little-explored nature of this integration in the field of patents.

These data help to assess the degree of maturity of the technologies analyzed, highlighting more consolidated areas and others that are still emerging, with room for new **innovations**.

Challenges and Opportunities

The integration of core-shell catalysts and the ALD technique in the development of SOFCs is a field that has yet to be fully explored, both in academia and in the technological arena. Patent analysis highlights this gap: only two records were identified that simultaneously address the

Table 5. Distribution of the legal status of the patent documents found.

“SOFC” AND “ALD”		“SOFC” AND “core-shell”		“ALD” AND “core-shell”		“SOFC” AND “ALD” AND “core-shell”	
Status	Quantity	Status	Quantity	Status	Quantity	Status	Quantity
Inactive	12	Inactive	2	Inactive	6	Inactive	1
Active	5	Active	5	Active	33	Active	1

three elements, one of which is active and the other inactive. This data reinforces the perception that this specific combination represents a technological frontier still in formation.

Despite the limited number, the most recurrent CPC codes (H01M2008/1293 and Y02E60/50) point to advanced electrochemical technologies and environmental mitigation, signaling the strategic potential of this combination. Individually, patents dealing with “ALD” and core-shell show greater frequency and predominance of active status, indicating continued interest in these areas.

These data, combined with a previous bibliometric study, help to paint a broader picture of the challenges and opportunities in this area. From a patent perspective, there is a notable scarcity of consolidated solutions that integrate the three technologies, hindering practical application. On the other hand, existing records demonstrate innovation and links to sustainability and energy efficiency. The growing interest in solutions applicable to the energy transition and the continuity of active filings reinforce the existence of room for innovation, especially with the joint engagement of academic and industrial efforts.

Thus, although still in its early stages, the combination of ALD, core-shell, and SOFCs shows promising fundamentals. Its advancement will depend on strategies to overcome technical barriers while taking advantage of the opportunities of an evolving technological landscape.

Conclusion

The analysis of patents involving “Solid Oxide Fuel Cell,” “Atomic Layer Deposition,” and “core-

shell” revealed different levels of technological maturity. The combination of ‘ALD’ and “core-shell” has the highest number of registrations, distributed across several countries and sectors, reflecting broad applicability and prominence in the innovation landscape. Combinations with SOFC, on the other hand, are less frequent, especially those combining all three terms, with only two registrations between 2019 and 2023.

Despite the low occurrence, one of the two documents remains active, indicating recent interest in protecting the technology. The associated CPC codes point to a link with electrochemical devices and energy conversion technologies. Most filings occurred in jurisdictions such as the US, Japan, South Korea, and EPO, covering national and international applications, evidence of global protection strategies.

Among the main filers are companies such as General Electric and LG Chem, as well as universities and research centers, reinforcing open innovation and the academic role in generating patentable technologies. The significant number of active patents suggests continued interest in ALD- and core-shell-based solutions, although still incipient in the context of SOFCs.

In the Brazilian case, only one deposit related to the combination of “SOFC” and “core-shell” was identified, with no records involving “ALD.” This low representation highlights a gap in the protection of advanced energy technologies and reinforces the need for policies that encourage applied research and its conversion into intellectual property assets.

In summary, the interface between ALD, core-shell, and SOFC represents an emerging niche, with

low current density but high innovation potential. The existence of active documents and strategic technical classifications indicates promising opportunities for institutions and companies wishing to explore this technological frontier.

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